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Ultrafast metal-semiconductor-metal photodetectors on low-temperature-grown GaN

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We have fabricated and characterized ultrafast metal-semiconductor-metal photodetectors based on low-temperature-grown (LT) GaN. The photodetector devices exhibit up to 200 kV/cm electric breakdown fields and subpicosecond carrier lifetime. We recorded as short as 1.4-ps-wide electrical transients using 360-nm-wavelength and 100-fs-duration laser pulses, that is corresponding to the carrier lifetime of 720 fs in our LT GaN material. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1938004]

Gallium nitride is a wide, direct band-gap semiconductor that makes it a very promising candidate for the fabrication of ultraviolet (UV) photodetectors. Various types of GaN photodetectors have been demonstrated recently, such as the Schottky barrier detector,[1] *p-n* junction,[2] *p-i-n* structure,[3] and metal-semiconductor-metal (MSM) photodiode.[4] Among these, MSM photodetectors exhibit superior performance in terms of the response speed, device noise, and fabrication simplicity. However, the GaN photodetector performance varied from sample to sample depending on the material quality,[5–8] in which growth temperature plays a major role. High quality GaN photodetectors with full width at half maximum (FWHM) of the response in the picosecond range (~3.5 ps), which are the best published data, were presented by Li *et al.*[9,10] In this letter, we present the fabrication and properties of MSM photodetectors based on low-temperature-grown (LT) GaN. Such material exhibits lower electron mobility and higher concentration of defects, thus subpicosecond carrier lifetime can be assumed, which essentially shortens the response time of these LT GaN photodetectors.

The photodetector structure was grown by plasma induced molecular beam epitaxy. An AlN/GaN/AlN/GaN heterostructure buffer with thickness of 100/1500/5/500 nm was deposited on 6H *i*-SiC substrate. Subsequently, the active GaN layer was grown at 650 °C with growth rate of 300 nm/h. Although the material is monocrystalline, the surface exhibits a roughness of about 20 nm and a high value of defects initialized by the low growth temperature instead of the usually used temperatures in the range of 750–900 °C.[11,12] The dislocation density is about 5×10^9 cm^{-2} that is 50 times higher than for conventional GaN. MSM structures with finger width and spacing of 1 and 1.5 μm, respectively, and an active area of 20×20 μm^2, as presented in Ref. 13, were patterned on the GaN surface using conventional photolithography and liftoff technique. The MSM electrodes consist of Ti/Al/Ni/Au (35/200/40/50 nm) for forming ohmic contacts. Ohmic contact metallization was annealed at 900 °C for 30 s. Devices with Schottky contacts (25 nm Ni, 300 nm Au) were fabricated for the sake of comparison. The whole surface except the MSM structures was coated with a 400-nm-thick SiO_2 layer. Ti/Au coplanar strip lines (CPS) with thickness of 50/600 nm were fabricated on top of this insulator layer.

Figure 1 shows typical current–voltage ($I-V$) characteristics of the photodetectors fabricated on LT-GaN material measured in the dark. The MSM photodetectors with ohmic contacts exhibit linear behavior in the whole bias range up to 100 V. The characteristics of the MSM photodetectors with Schottky contacts is more complex. It is defined by the reverse current of a Schottky contact above GaN with a high defect density. Furthermore the free carriers are collected at a different thickness of the layer structure with different bias voltage. Rapid increase of the dark current at higher bias is due to the collection of carriers in the deeper regions of GaN

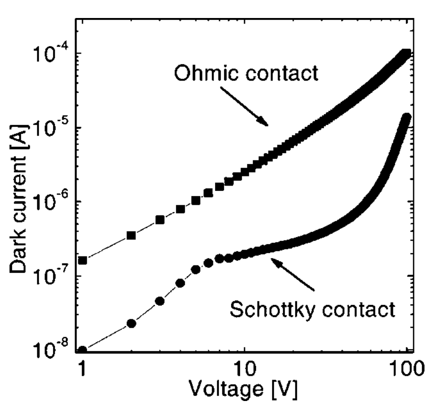

FIG. 1. Current–voltage ($I-V$) characteristics of the MSM LT GaN photodetectors with ohmic and Schottky contacts, with active area of 20×20 μm^2 and with finger width and spacing of 1 and 1.5 μm, respectively.

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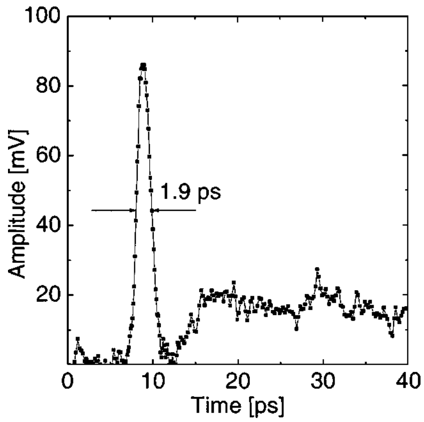

FIG. 2. Time-resolved photoresponse waveform for the MSM LT GaN photodetectors with ohmic contacts (active area: $20\times20\ \mu m^2$, finger width and spacing: 1 and 1.5 μm), measured at 10 V bias and 5 mW input power.

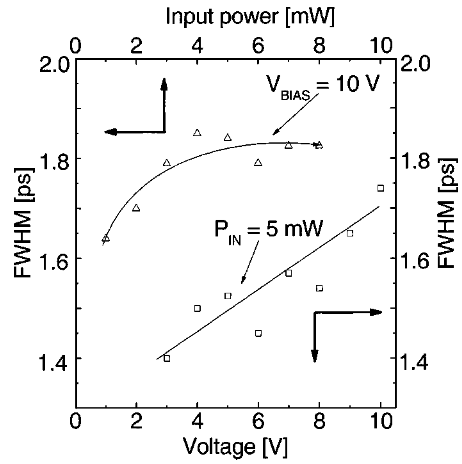

FIG. 4. FWHM of electrical transients of the LT GaN photodetector as a function of bias voltage and input power.

under the AlN layer. The temporally resolved photoresponse of the devices was measured under the illumination with 100-fs-wide, 360-nm-wavelength, 80-MHz-repetition rate optical pulses from a commercial Ti:sapphire laser. The photoresponse waveforms were recorded with the help of an electro-optic (EO) sampling system, featuring ~200 fs temporal resolution.[14] Electrical transients were sampled at a spot on the CPS line located ~30 μm away from our device. The time-resolved photoresponse waveform of MSM photodetectors with ohmic contacts measured at 10 V bias and 5 mW optical input power is shown in Fig. 2. Photodetector response exhibits full width at half maximum (FWHM) of about 1.9 ps with amplitudes up to 85 mV. With the calculated RC time constant of 1.2 ps, the carrier lifetime is assumed to be about 1.4 ps at 10 V bias and 5 mW optical input power.[14] To evaluate the measured pulse amplitude: the obtained value for an optimized low temperature grown GaAs photodetector with the same layout and under the same operation conditions (bias voltage: 10 V, optical input power: 5 mW) is 700 mV.[13] Because of the lower wavelength of 360 nm at the GaN measurements, compared to 810 nm for GaAs, the same optical input power gives only 44% of incident photons for GaN compared to GaAs. Furthermore, the 360 nm wavelength is only 5 nm above the band gap of GaN.[9] Considering both facts, the sensitivity of the LT-GaN detector is comparable to the devices based on LT-GaAs.

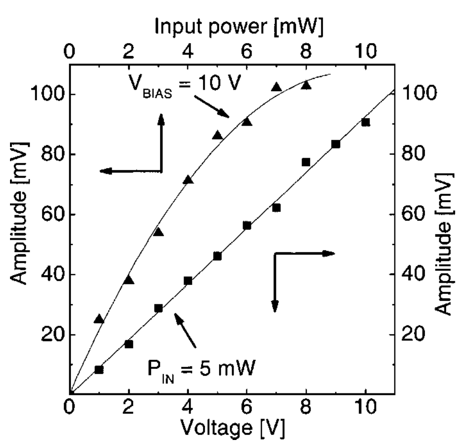

FIG. 3. Photoresponse amplitude of the MSM LT GaN photodetector as a function of bias voltage and optical input power.

Figure 3 presents the photoresponse amplitude of the photodetector as a function of bias voltage and optical input power. We observe that the photoresponse amplitude increases linearly with increased bias voltage. The dependence on input power is linear for low power and gradually approaches saturation. We attribute this saturation and also the increase of the FWHM with increasing input power observed in Fig. 4 to heating of the device by the optic input power and by the photocurrent. The same behavior is observed when the bias voltage is increased: the FWHM increases for about 25% with a change of the bias from 3 to 10 V (Fig. 4). Beside the effect of heating, the increase of the FWHM by increasing the bias can also be caused by an increase of the carrier life time due to a reduction of the electron capture cross section with increased electric field, as it was observed earlier by Zamdmer and Hu in LT GaAs.[15] At 3 V bias and 5 mW input power, we recorded 1.4 ps-wide-electrical transient that is the shortest measured ultraviolet response for a GaN photodetector reported to date. We must stress, however, that the effective carrier lifetime in our LT GaN materials is extended from ~720 fs to ~1.4 ps at high bias and intense input power because of the effects mentioned above. These values are extracted from the experimental results using the method mentioned in Ref. 14.

In conclusion, we have fabricated ultrafast MSM photodetectors on LT GaN grown by plasma induced molecular beam epitaxy. The devices exhibit a peak amplitude up to 100 mV with FWHM as short as ~1.4 ps photoresponse under illumination by 100-fs-wide and 360-nm-wavelength laser pulses. These results show that LT GaN material is a promising candidate for high speed UV photodetectors.

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